MEMS RELIABILITY ASSURANCE ACTIVITIES AT JPL

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ABSTRACT

An overview of MEMS reliability assurance and qualification activities at JPL is presented along with the a discussion of characterization of MEMS structures implemented on single crystal silicon, polycrystaline silicon, CMOS, and LIGA processes. Additionally, common failure modes and mechanisms affecting MEMS structures, including radiation effects, are discussed. Common reliability and qualification practices contained in the MEMS Reliability Assurance Guideline are also presented.

INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) devices and structures are a key enabling technology for creating cost-effective, ultra-miniaturized, robust, and functionally focused sensors and actuators for space applications. However the reliability of MEMS devices for space applications has not been established and qualification requirements have not been clearly defined. Process characterization and determination of active failure mechanisms affecting this new and promising technology are critical to understanding the reliability of MEMS processes and are determining factors in the suitability of this technology for insertion and application in high reliability systems. Here, we present our general approach for understanding MEMS reliability issues and related failure mechanisms. In addition, we present the current MEMS reliability assurance activities at JPL along with a discussion of the "MEMS Reliability Assurance Guideline for Space Application" which was developed to help users and manufacturers of MEMS devices.

MEMS RELIABILITY ACTIVITIES

The approach at JPL for understanding the MEMS reliability issues and related failure mechanisms has been concentrated around three general activities. Process characterization, environmental test and characterization, and the identification of MEMS related failure modes and mechanisms.

PROCESS CHARACTERIZATION

In order to ensure robust operation, reliability and process test structures designed to provide information on the stability of the manufacturing process, material characteristics and the reliability of the structures, are utilized. It is the analysis of these test structures which will enable the insertion of advanced MEMS devices into designs with a high degree of confidence in their reliability. At JPL, reliability and process monitor test structures have been utilized to understand process stability and help identify common failure modes and mechanisms of the processes and designs under consideration. This activity has been carried out in collaboration with our MEMS Reliability Assurance Alliance partners where the design , fabrication, test and characterization of the structures are performed by various partners and the data shared for the benefit of the whole. Examples of these test structures include, Beam Stubs to indicate process stability, Resonant Beam Structures (Figure-1) to measure beam stiffness, Cantilever Beams used to measure stresses, and Stress/Strain Gauges used to measure residual stresses.

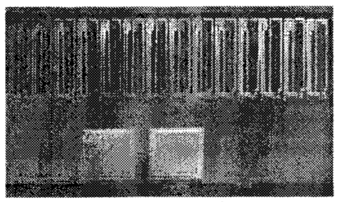

Figure 1: Resonant beam array

ENVIRONMENTAL CHARACTERIZATION

Long term reliability and survival of MEMS devices require effective demonstration of reliable and robust operation in the intended mission environment. The purpose of environmental verification and testing of a device is to demonstrate the quality and reliability of a design and its suitability for the intended application, and to screen for manufacturing workmanship defects. For space applications, the purpose is also to simulate the launch environment and to qualify the design for launch and in-serive conditions.

An environmental verification and testing program typically involve a series of dynamic and thermal tests, which include pyroshock, acoustic noise, acceleration, random and sinusoidal vibrations; and thermal-vacuum, thermal dwell, and thermal cycling. For devices that are sensitive to electromagnetic fields, an electromagnetic compatibility test should be conducted. Evacuated, sealed MEMS packages generally undergo a pressure leak test to ensure the integrity of the packaging. For MEMS devices operating in the radiation field of space, radiation testing is also recommended. This program should be designed to characterize the device for a specific application.

The JPL micro-gyroscope (Figure-2), developed for application in a miniaturized inertial navigation unit, consists of four single crystal silicon square cloverleaves. The structure, 4mm wide by 26 microns thick, is suspended from the substrate by four silicon springs. In the center is a brass post, 4mm tall, which provides gyroscopic motion for the sensor. Two of the four cloverleaves are used as oscillators to move the post along the x axis, while the other two cloverleaves are used as sensors to detect rotational deviations in the path caused by Coriolis forces. The majority of stress upon the device occurs along the spring edges, as they experience the greatest strain from device motion. With the sensitivity of this device largely dependent upon the Q of the structure, and thus its resonant frequency, the structural integrity of the springs is vital to maintaining optimal device performance and is thus an area of great survivability concern.

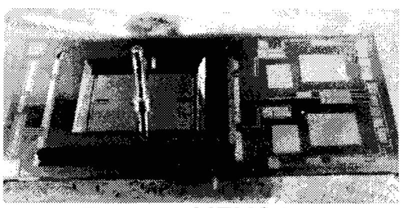
Figure 2: MEMS Microgyro

The devices were exposed to an environmental vibration profile to satisfy the X-33 launch environment [1]. This was equal to a three minute vibration test along the x and z axes using a B&W BW-100C2 vibration bench. On each device, the z axis was subjected to the out-of-plane vibration spectrum, followed by the x plane being exposed to the in-plane vibrations. After each test, the gyroscopes were carefully examined for any signs of structural failure. The vibration profile tests were repeated to verify the suitability of the devices for this launch environment.

MEMS RELIABILITY GUIDELINE

The "MEMS Reliability Assurance Guideline for Space Applications" was developed as an aid to help in the understanding of MEMS reliability and to facilitate the insertion of this technology into high reliability applications [2]. The guideline is structured as an educational guide, offering descriptions of the most common device structures and technologies and the steps required to meet the demands of the space environment. The document is intended as a reference for understanding the various aspects of MEMS with emphasis on device reliability. Material properties, failure mechanisms, processing techniques, device structures, and packaging techniques common to MEMS are addressed in detail. Additionally, design and qualification methodologies provide the reader with the means to develop suitable qualification plans for insertion of MEMS into the space environment.

FAILURE MODES AND MECHANISMS

A critical part of understanding the reliability of any system comes from understanding the possible ways in which the system or its element may fail. In MEMS, there are several failure mechanisms that have been found to be the primary sources of failure within devices. In comparison to electronic circuits, these failure mechanisms are not well understood nor easy to accelerate for life testing. The activities at JPL have concentrated on identifying failure modes and related mechanisms relevant to MEMS structures and processes of interest [3,4]. In this process, the most common failure modes were identified and related to their sources. Some examples of the failure modes include the following:

STICTION

One of the biggest problems in MEMS has been designing structures that can withstand surface interactions[6]. This is due to the fact that, when two polished surfaces come into contact, they tend to adhere to one another. While this fact is often unimportant in macroscopic devices, due to their rough surface features and the common use of lubricants, MEMS surfaces are smooth and lubricants create, rather than mitigate, friction. As a result, when two metallic surfaces come into contact, they form strong primary bonds, which joins the surfaces together. This is analogous to grain boundaries within polycrystalline materials, which have been found to be often stronger than the crystal material itself. However, adhesive boundaries are usually not as strong as grain boundaries, due to the fact that actual area of contact is limited by localized surface roughness and the presence of contaminants, such as gas molecules.

In most MEMS devices, surface contact causes failure. When MEMS surfaces come into contact, the Van der Walls force is strong enough to irrevocably bond the two surfaces (Figure-3). Although some devices, such as micro-switches, are designed to combat this problem through strong actuator networks, most devices must be designed to eliminate any surface interactions, in order to avoid the effects of undesired surface adhesion and stiction.

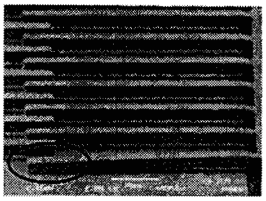

Figure 3: Polysilicon cantilever adhering to substrate

VIBRATION INDUCED FAILURES

Due to the sensitivity and fragile nature of many MEMS structures, external vibrations can have disastrous implications. Either through inducing surface adhesion or through fracturing the device support structures, external vibrations can cause catastrophic failure. Long-term vibration will also contribute to fatigue. For space applications, vibration considerations are important, as devices are subject to large vibrations in the launch process (Figure-4). Identifying the physical limitations of various test structures and devices through environmental test and characterization under controlled conditions has provided a better understanding of this failure mode and it's related mechanisms.

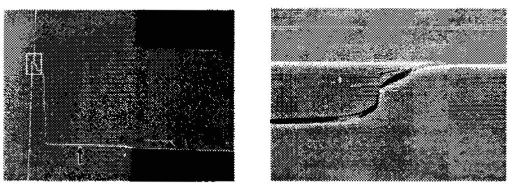

Figure 4: Cracks in single crystal silicon support beams caused by vibrations from a launch test.

RADIATION EFFECTS

While still in its infancy, the field of radiation effects on MEMS is becoming increasingly important. It has long been known that electronic systems are susceptible to radiation, and recent research has raised the possibility that mechanical devices may also be prone to radiation induced damage. Especially sensitive to total ionizing dose (TID) radiation will be devices that have mechanical motion governed by electric fields across insulators, such as electrostatically positioned cantilever beams. The cumulative radiation-induced deposition of charge can cause a shift in electrical behavior of the insulator which, in turn, alters the cantilever deflection.

Since biased insulators are also susceptible to dielectric rupture caused by energetic, charged ions, there is a distinct possibility that these devices will have decreased performance and even catastrophic failure in the space environment due to interactions with galactic cosmic rays (GCRs) and high energy protons.

A further complication is the fact that high levels of radiation can cause bulk lattice damage and make materials more susceptible to fracture. This effect, called displacement damage, is due to collisions of bombarding radiation particles, such as protons, electrons, neutrons and heavy ions, with lattice atoms in metals and semiconductors. Displacement damage-induced alterations in the Si on which the MEMS is fabricated can also change the electrical characteristics of the Si and hence the behavior of the MEMS.

Of particular importance for establishing radiation hardness assurance (RHA) for MEMS is the fact that microelectronic devices are often integrated on the same chip or substrate as the mechanical portion of the MEMS, and these devices can be much more susceptible to radiation than the microelectromechanical device itself. This is especially important when considering the use of commercial-off-the-shelf (COTS) MEMS in space systems.

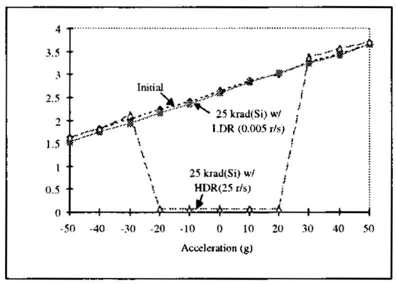

Figure 7: Effect of total ionizing dose on output of an ADXL50 microaccelerometer [6].

Recent work confirming that dielectric layers will trap radiation-induced charged particles, creating a change in electric field [5,7], is illustrated in Figure 7. This permanent field effect will change resonant characteristics and alter the output of many sensors. As shown in Figure 7, test results of a group of surface micro-machined devices exposed to gamma radiation exhibit radiation-induced effects that are different from the usual response of CMOS devices to radiation. In addition, there is a dose rate effect as shown by comparing the two curves for 25 krad irradiations.

REFERENCES

1. B. Stark, R. Lawton, D. Vu, S. Kayali, "A survivability Study on a Microgyroscope Involving Laser Interfermetery" JPL D-15753, December, 1997.
2. B. Stark., "MEMS Reliability Assurance Guideline for Space Applications", JPL ~~Publication,~~ 1998 D-16460

3. B. Eyre and K. Pister, "Micromechanical Resonant magnetic Sensor in Standard CMOS", 1997 International Conference on Solid State Sensors and Actuators, Chicago, June 16-19, 1997.
4. B. Stark and R. lawton, "Reliability Investigations on a CMOS Magnetometer" JPL D-15768, December, 1997.
5. C. Barnes, A. Johnston, C. Lee, G. Swift, and B. Rax "Recent Radiation Effects Activities at JPL: Coping with COTS" Proceedings of the Third ESA Electronic Components Conference, ESTEC, Noordwijk, The Netherlands, 22-25 April 1997.
6. K. Man, R. Ramesham, B. Stark, "A resource Handbook for MEMS Reliability" JPL D-16171.
7. C. Lee, A. Johnston, W. Tang, C. Barnes and J. Lyke, "Total Dose Effects on Microelectromechanical Systems (MEMS): Accelerometers", Trans. Nuc. Sci. **43**, 3127 (1996).

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